Space Launch Vehicles

by Patrick H. Stakem

Number 16 in the Space Series

Table of Contents

Introduction

This book covers the topic of launch vehicles, and their support facilities. These are generally rocket powered, but there are other options. Not everything rocket-powered is going to space, either. They have been rocket-powered motorcycle,s and cars. We're not going to talk about those, in this book. And, we are certainly not going to mention the Rocket Racing League.

This is not a comprehensive coverage of launch vehicles. We will not discuss military systems, except if they are used or re-purposed to civilian spaceflight. We will cover the spectrum from small sounding rockets to heavy lift vehicles. We will look at other options to get to orbit, including air-launch systems, the space elevator, and balloon-borne payloads.

The book does not specifically cover sounding rockets.

Author

The author has a BSEE in Electrical Engineering from Carnegie-Mellon University, and Masters Degrees in Applied Physics and Computer Science from the Johns Hopkins University. During a career as a NASA support contractor from 1971 to 2013, he worked at all of the NASA Centers. He served as a mentor for the NASA/GSFC Summer Robotics Engineering Boot Camp at GSFC for 2 years. He teaches Embedded Systems for the Johns Hopkins University, Engineering for Professionals Program, and has done several summer Cubesat Programs at the undergraduate and graduate level.

His hands-on rocketry experience dates from 1962, with model rocketry in high school. He has actively been studying rockets, building them, getting them to launch payloads, for over 50 years. Model rocketry is a safe and ideal practice for a STEM curriculum. He overlapped Werner von Braun who was Vice President of Engineering at Fairchild. So, technically, he was once a member of the Von Braun team.

A note on Units

I am fairly conversant in both English and Metric units (what is the metric equivalent of furlongs per fortnight?). Metric (SI) is mandated for NASA

usage now, for interchangeability with our partner space faring nations. When a lot of the legacy flights discussed here were flown, English units were the norm. I have tried to keep the units comparable to the mission at the time. Conversions are easy enough, but units conversion is a source of error. It's not what you know about units and measurement, its how you think. And, I still think English units (even the English use Metric now), and convert in my head or on my phone.

For scientific/engineering work, the Metric system is well thought out. For artisans, the English system served well, as most units were divided by 2, which is easy. Fold the cloth. Hopefully, when we are all taught Metric first, some one will still remember the conversions. You just need a slide rule....

Rocket Engines

Rocket engines come in two flavors – liquid propellant, and solid propellant. Each has its advantages and disadvantages. Liquid engines are throttle-able, and can be turned off and re-ignited. Once you light off a solid, it burns to the end of the propellant. This means you can test-fire a solid, but then it's used up. A liquid engine can be test-fired multiple times, and then used.

There are actually hybrid models, with solid fuel, and a liquid oxidizer. Spaceship One, the Scaled Composites Model 316, uses a hybrid engine from SpaceDev. It has a solid, rubber-like propellant, and nitrous oxide. The engine can be shut down after it is started, but it is not throttle-able. It has a total burn time of around 80 seconds.

A figure of merit for rocket engine performance is Specific Impulse (Isp) with units of seconds. Impulse is change in momentum per unit of propellant used. Higher specific impulse engines are more efficient.

Cyrogenic propellants provide the best efficiency, with the choice of liquid hydrogen fuel (-253C) and liquid oxygen (-183C). Methane is being phased in in place of hydrogen, and has some advantages.

Space, by definition is 100 km in altitude. At that altitude a jet engine will not function, due to insufficient oxygen.

The rocket engine's main job is not lifting weight to orbital altitude, it is getting the payload to the speed of 8 kilometers/second, orbital velocity. You can't do that in the thick lower atmosphere, since the payload would be heated by air friction, and burn.

In an atmosphere, you can use air breathing engines, but not for long. Jet engines, like on the X-15's B-52 motherships, got the craft up high and moving fast, so it could reach the limits of space. In a sense, the B-52 was the X-15's first stage.

A similar technique was developed by famed designer Burt Rutan, for Scaled Composites. The purpose-built carrier vehicle, White Knight, carries the smaller SpaceShip to a high altitude,. At this point the two vehicles separate, and the White Knight fly's back to a runway landing as the smaller craft continues to orbit with its rocket engine.

The X-1 rocket plane was built in the U.S., and flew in 1947. Chuck Yeager took it beyond the speed of sound, the first human to get going that fast. The X-1 was thirty feet long, with a wing area of 130 square feet. Empty weight was 7,000 pounds, 12,225 pounds loaded. Theoretical maximum speed was Mach 1.25. The engines could operate for 5 minutes on the supplied fuel, and then the X-1 became a very fast glider. It could reach 72,0000 feet, not quite space. It was carried to altitude by a B-29.

The X-1 used the XLR-11 engine from Reaction Motors, producing 6,000 pounds-force from ethyl alcohol and liquid oxygen. It had four combustion chambers that could be operated independently, but were not capable of being throttled.

The best rocket fuel is liquid hydrogen and liquid hydrogen. Unfortunately, these need to be kept ultra-cold, or they expand into a gas and over-pressurize the fuel tanks.

We really want the launch vehicle to be reliable, and get our really expensive payload to orbit. The games changes a lot when there are crew onboard. Human rating is time consuming, expensive, and necessary.

On the Shuttle, as a default, all payload carried to orbit had to be human rating. I presented a lot of GSFC's Shuttle payloads to the Safety Panel at

Johnson Space Center.
A lot of liquid fuel rockets use RP-1 (Rocket Propellant-1) which is a very refined petrochemical, related to jet fuel. It's problem is its non-conductive, so it builds up static charge. That's a bad thing, as it can provide an ignition source. It is normally treated with an anti-static agent, anti-icing, and anti-corrosion agents.

Alcohol can be used, and was applied to the V-2 by the Von Braun Team, more out of a war-time scarcity of petrochemicals.

Also, it is common to see multiple engines, a technique termed clustering, rather than one big engine. Not everything scales well, and the existing engines are proven technology.

My favorite fuel is Red Fuming Nitric Acid (RFNA). It is hypergolic with hydrazine, meaning they burn or explode when in contact.

KSC Pad safety training tells you that if you see a low level brown cloud, try to run at right angles to its direction, If that cloud catches up with you, everything will dissolve, and they might find your corroded belt buckle.

Command and Control

Ballistic Missiles of the 1960's Cold War relied on ground based radar tracking, and ground based computers to adjust their trajectories. The trajectory could only be adjusted during powered flight, by gimballing the engines. These only needed to work for 2 minutes after launch, when the engines burned all he fuel. The two that I have hands-on experience with are the Atlas's AN/GSQ-33, Burroughs SM-65 and the Titan-I's Athena. The Bomarc, more of an anti-aircraft cruise missile, was directed against enemy aircraft by the 250 ton SAGE computer, in an underground bunker. Since it was air-breathing (jet, not rocket) it could be continuously guided to the target. None of these were ever used in anger.

The Redstone missile, that will be discussed later, had an inertial guidance unit onboard, and could adjust its own attitude. That was used as a model for the control unit in the Jupiter missile. The Titan-II used an onboard guidance computer, which is the norm today. The Titan's unit was an IBM-ASC-15, later replaced by a Delco 352. Delco computers were also used onboard the Delta rocket.

Historic Vehicles

This section discusses historic predecessors using rocket engines, starting with the German V-2 Project in World War-II.

V-2

Although the Americans, the Russians, and the Germans were experimenting with rockets from the 1920's, the German efforts, spurred on by World War-2 stand out. The V-1, what we would now call a cruise missile, was guided by a simple distance-measuring device driven by a small propeller. It required pre-calculations, what the artillery people call firing tables. You launch from a known position in a known direction. When the distance counter triggered, the missile was put into a steep dive into the target. But the missiles flew low and slow, and many were shot down (some by the Author's father), or were simply flipped out of control by fighter planes. They were not, by any means, an accurate weapon.

The V-2 was a true ballistic missile, developed by the Von Braun team at Peenemunde. Not only did they develop the world's first operational ballistic missile during wartime, but they managed to turn it over to the Army for use in the field. Quite a few were fired against England and the Port of Antwerp with devastating effect. There was no practical defense.

Internal guidance with gyroscopes was used, with the SG-66 Unit. The missiles were launched from a pre-surveyed location in a precise direction. A known distance to the target determined the engine burn time, which was set into the vehicle before launch. After that, no changes were possible. It was inaccurate, but devastating when it worked. One of the SG-66 in the Smithsonian's Air & Space holdings. It was developed in 1936 by Dr. Fritz K. Miller. He went on to develop the gyro platform for the Saturn rocket.

The German V-2 Field Operations Manual was captured by US forces along with missiles and launch and ground support equipment. The manual was translated at the Army's Aberdeen Proving Grounds (MD). It tells the ground troops how to launch the missile. The manual assumes a high school education. After the launch site is accurately surveyed, the missile was erected and fueled. Then, the troops were instructed to "… point fin number one towards London…" The distance was set into the timer that would shut down the engine, the missile was launched, and the support equipment made a hasty withdrawal to avoid Allied air power.

This approach was hardly changed as late as the First Iraq War. Captured V-2's were used in Project Hermes, but a need was seen to produce vehicles based on the V-2, as the supply of captured rockets was going to run out. Also, the V-2's were never meant for research, and tumbled at high altitude, They were designed as weapons, and carried a rather large payload, one ton. This was way in excess of the science payloads, leading to the launch of a lot of lead ballast.

Viking

The Viking was designed to replace the V-2's as a science payload carrier. It was half the size, in terms of mass, and power. Both used active guidance, and the same fuel and oxidizer (alcohol and Lox). The Viking used the Reaction Motors XLR10-RM-2, producing in excess of 20,000 lbf of thrust. It improved on the V-2 design, by removing the graphic vanes in the exhaust for steering, and using a gimballed nozzle. Control in the roll axis was by turbo-pump exhaust through jets on the fins. An aluminum skin in place of steel was used, and the tanks were a structural element. The Viking was a bit longer, but more slender. They had a better mass ratio, the ratio of fueled to empty weight. Vikings were launched from the deck of the USS Norton Sound at sea. By 1951, the Viking beat the standing V-2 altitude record by travelling to 136 miles.

Vanguard

The Vanguard rocket was a Navy Program to place satellite in orbit. Project Vanguard ran from 1957 to 1959, but the Soviets were the first to orbit. There were eleven attempted launches, with three successful satellites in orbit. At the time, although it had never been done, there were three U. S. candidate rockets for putting a satellite in orbit. These were the Air Fore's Atlas, the Army Ballistic Missile Agency Redstone, and the Navy variant of the Viking sounding rocket, built by the Glenn L. Martin Company for the Naval Research Laboratory. Redstone, a three stage vehicle, had a capacity to orbit of 9 kilograms. The vehicle had no fins, but used gimballed engines on the first and second stages, and the third stage was spin-stabilized. Note also that second stage engine nozzles ("bells")are wider than first stage ones. This is because they operate higher up, where the atmosphere is thinner. This allows for a better and quicker expansion of the exhaust gas.

The first two Vanguards tested were actually two left-over Martin Viking RTV-N-12a, testing telemetry, separation, and ignition of the upper stage.

The first stage used a General Electric X-405 liquid fuel engine (LOX and kerosene) with more than 30,000 lbf of thrust. The second stage used an Aerojet General AJ10-37, 7600 lbf of thrust, and using nitric acid and UDMH. The third stage used solid fuel, and was supplied by the Allegany Ballistics Laboratory. It had 2,600 lbf of thrust.

The first real Vanguard was already launched with inert upper stages. By then, the Soviet satellite was in orbit. There was a chance the next test flight could have put a U.S. Satellite in orbit, but it only reached an altitude of 1.2 meters, before it exploded. The satellite was still transmitting from nearby bushes. The fourth try was the winner, and the the satellite and its third stage remain in orbit to this day, the oldest man-made artifacts in space. It's a high orbit, so they should remain recoverable for hundreds of years. Let's crowd-source a project to bring them back to the Smithsonian. Two more Vanguard satellites were placed in orbit before the end of the program. In total, Vanguard had a dozen successful launches, from 1957 to 1959.

Ballistic Missiles, repurposed

The early missile guidance computers were located in underground bunkers, and transmitted their steering commands to the missile via a radio link. The missiles of the day had no inertial guidance (and, GPS was years in the future), and went ballistic after the engine burned out, a period of just several minutes. After that, the laws of physics took over.

Corporal

The MGM-5 Corporal was a tactical ground-to-ground missile, the first certified to carry a nuclear warhead. It was developed at the White Sands Missile Range. It was liquid fueled, using red fuming nitric acid and hydrazine. It was replaced by the MGM-29 Sergeant in 1963.

The Private had been developed at the California Institute of Technology's Guggenheim Aeronautical Laboratory for the Army. This facility was to become the Jet Propulsion Lab. The Private was based on solid fuel JATO

units, that allowed heavily loaded bombers to get in the air.

The Corporal was transformed from a weapon of war to a civilian sounding rocket by Douglas aircraft. It remained liquid fueled, but a *Tiny Tim* solid rocket booster was added. At the White Sands missile range, in 1945, a WAC-Corporal reached 50 miles in altitude, where a captured V-2 reached 70 miles. The WAC part of the name was a tribute to the Women's Army Corps. Some say it really meant “without attitude control.”

The two stage rocket was 24 feet long and 30 inches in diameter, with four fins. The booster only burned for about half a second, getting the rocket up and going for a 47 second burn. There is an example on display at the Smithsonian's Air and Space Museum.

Redstone

Redstone refers to a family of launch vehicles, 1950-1960's, developed at the Army's Redstone Arsenal in Huntsville, AL. The Juno variation launched the U.S.'s first satellite in 1958, and the Mercury Redstone launched the first U.S. Astronauts. The extended Redstone family included the Jupiter, Juno, and Saturn. It traced its design back to Von Braun's V2.

Before the Mercury capsules were launched with astronauts, they were tested using the Little Joe launch system. Later un-crewed Apollo capsules used the Little Joe-II. These used a cluster of four Sergeant solid fuel rockets. They were produced by North American Aviation. They could launch the space capsule on a ballistic trajectory 100 miles high, from the Wallops Flight Facility in Virginia.

The Redstone, built by Chrysler Corporation was first launched in 1953. It used a Rocketdyne engine, with 78,000 pounds- force. The vehicle was developed at the Army Ballistic Missile Agency at Huntsville, Alabama. It used a mixture of water and ethyl alcohol for fuel, and liquid oxygen,

Jupiter-C

Jupiter-C was a sounding rocket member of the Redstone family from the Army's Ballistic Missile Agency in Huntsville, Al, developed by von Braun and his team. The first stage was a stretched Redstone with larger

tanks, and the Rocketdyne A-7 engine. The second stage used a cluster of eleven solid fuel Sergeant rockets. The third stage used a cluster of 3 solid rockets. Before launch, the third stage was spun, eliminating the need for a control system. It was used for three sub-orbital flights in 1956-57. It was then used for three satellite launches from the Cape.

Jupiter-C was a modified Redstone. The Redstone's tanks were stretched by 8 feet to get more propellant capacity. The second stage included eleven Sergeant solid rockets. The third stage had 3 of these. Upper stage guidance was done by spin stabilization, a system developed by Wernher von Braun. Juno-1 had a fourth stage, consisting of a single solid rocket.

Juno

The Juno was a four-stage launch vehicle, derived from Jupiter-C. It had the distinction of launching the U.S.'s first satellite in 1958. The Jupiter-C was extended by an additional stage, which was rotated before launch to provide passive stability, with additional payload capacity to orbit. The Jupiter and Juno were actually the same height, with the 4th stage of the Juno contained in the nose of the third stage. Juno went on to successfully launch two more Explorers, but an additional two did not achieve orbit. It was built by Chrysler Corporation for the Army Ballistic Missile Agency.

Mercury-Redstone

The Mercury-Redstone used a stretch configuration for Project Mercury's sub-orbital launches, including two crewed launches in 1960/61, following Ham the chimpanzee's flight.

Sparta

The Sparta vehicle was built from surplus Redstone's, with added solid fuel upper stages. It could send 45 kilograms to low Earth orbit. There were a total of 10 launches, 9 successful. A Sparta configuration launched an Australian satellite to orbit.

Atlas

The Atlas ballistic missile was a family of launch vehicles, transitioned from weapons systems, “man-rated”, and used for the crewed Mercury flights, as well as for many satellite launches. It was designed in the 1950's as Project MX-1593, and built by the Convair Division of General

Dynamics. It's engines burned RP-1 (basically refined kerosene) and Lox. It had three engines in a unique stage-and-a-half configuration. The outer two booster engines were jettisoned, and the center engine continued the mission. They were all fed from the same tanks. Atlas launched the first 4 astronauts to orbit. From 1991 through 2004, there were 63 Atlas launches. The current generation, the Atlas-V, remains in service. More than 300 launches have left Kennedy Space Center, and 285 from Vandenberg Air Force Base in California. Many ICBM models were used for the civilian missions, after the Atlas was retired from military service.

The Atlas was the result of the von Neumann ICBM Committee. Atlas A, B, C, and D had no onboard computers and used ground-based guidance Atlas was the first intercontinental ballistic missile deployed by the United States, Weapon System 107A-1, in 1955.

The early series, Atlas-1, was built by Lockheed. These were used for 40 years, 1957 through 1997.

The launch capability to LEO of the early Atlas's was 5,900 kg. The Atlas-2 improved this to 8,600. The Atlas-III could do 10,800kg. Atlas-V improved this to 18,850 kg. The early models were built by Lockheed. The current -V model is by United Launch Alliance, a joint venture of Lockheed and Boeing.

The AN/GSQ-33, Burroughs SM-65 was the ground-based guidance computer for the early Atlas series of rockets. Eventually 17 units were delivered. The ones at the Eastern Test Range (Cape Canaveral) and Western Test Range (Vandenberg AFB) were used for range safety until 1978. The reliability specification was 0.96, but the machine achieved an operational reliability of 0.998. There were no errors during flights. One machine operated 24 hours per day continuously for 17 months without a critical failure. The specified minimum specification for reliability was 0.96. The achieved value was 0.998.

The Atlas design required that the fuel and oxydizer tanks remain pressurized, or the unit would collapse. When not fueled, nitrogen gas was used. The tanks were built of thin stainless steel to save weight, and were not even painted. It was required to keep the skin oiled to prevent rust. For this, a special oil was developed, WD-40. Whatever happened to WD-39?

The Agena upper stage was adapted to the Atlas. That unit used hypergolic propellants, which self-ignite when mixed in the combustion chamber. Agena's were sent to orbit to serve as rendezvous and docking targets for the Gemini missions. The technique was critical for the later Apollo lunar missions.

The Atlas-Centaur used a liquid hydrogen-liquid oxygen upper stage. The Atlas SM-65D had to be reinforced to carry the weight. It used the dual Launch Pads of Launch Complex 36 at Kennedy Space Center. It has been in use for 50 years. It is based on the Atlas design, requiring pressurized tanks. The stage has one or two RL10 engines. A Centaur was scheduled to fly on the Shuttle with great debate concerning safety, but the Challenger accident shut that down.

The Atlas-3, controversially uses Russian Energomash RD-180 engines, developing 860 kilo-pounds-force. The Russian origin became a concern for Congress, relying on a foreign supplier of critical space parts. The Atlas-V, currently in use, continues to rely on the Russian engines, with a Centaur upper stage with a single or dual motors.

In 2014, the U. S. Congress prevented any further military launches on vehicles with Russian engines. There were 29 motors on order at the time, and their use for civilian payloads was approved. Russia also had concerns about using their engines to boost U.S. Military payloads to orbit. In the mean time, the U.S. Is struggling to build its own replacement motor. This may actually come from the private sector, as Blue Origin's BE-4 engines, using LOX and methane, may fit the specification.

The RD-180, currently in use by Russia and the United States, is used for the Atlas-V. It has two combustion chambers, and dual nozzles. It achieves 860 kilo-lbf. The earlier RD-170 engine was used in the Russian Energia rocket. They are still in use with the Zenit launch vehicle. The Energia lifted the Russian shuttle Buran to orbit.

Titan

Titan refers to a family of rockets, dating back to 1959. It has seen over 370 launches, most notably the crewed Gemini missions in the 1960's.

Titans were originally developed as ICBM, for Air Force use. They were de-comissioned in 1987, but are still in use for military and civilian payloads.

Titan-I

Identified as HGM-25A, the Titan-I was developed as a backup to the Atlas missile, It is a two stage vehicle, using RP-1 and Lox. The guidance computer was the Athena, designed by Seymour Cray. The author is very familiar with this unit. In the 1960's, missile guidance computers were developed that could adjust the trajectory after launch, but only during powered flight. The author has direct hands-on experience with both machines.

Until the technology advanced far enough to allow guidance computers to be miniaturized and installed inside the missile, the ground based guidance computer was a necessary part of the missile system.

The Athena was the ground-based computer for the Titan-I missile. These units were not for flight; they exceeded weight budget by 9 tons. The idea of putting the computer onboard the vehicle was just a dream at this point.

The Univac Athena required 370 square feet of floor space underground in a hardened bunker. Using radar data input, it calculated course corrections during engine burn. It only had to work for two minutes. It was programmed in assembly language, and was a Harvard architecture, meaning the instructions and data were kept in different stores. In the case of the Athena, the instructions were kept on a magnetic drum, and the data was kept in core.

The Athena cost about $1,800,000. when new, and weighed over 18,000 lbs when shipped. The Athena used a massive motor-generator set with 440-volt 3-phase AC input. The motor generator control unit weighed a ton, and the motor/generator itself weighed over 2 tons. I managed to wire one of these up correctly, once.

The Titan launch complex was located underground, and a single Athena could be used with multiple missiles, launched one at a time. There were eighteen missile complexes in the U. S., each capable of launching

multiple missiles. The liquid-fueled Titan's were considered to be only a stop-gap measure pending the deployment of the solid fuel Minuteman Missile, and none of the complexes were operational for more than four years.

Titan-II

The Titan-II was used extensively by NASA as a heavy lift vehicle, and was the launch vehicle for the manned Gemini missions. The guidance system was supplied by A. C. Spark Plug, a Division of General Motors, based on an MIT design.

The Titan-II used the IBM ASC-15 guidance computer. The ASC-15 had a drum memory, and occupied a volume of 1 x 1 x 1.5 feet. The data storage drum was 3 inches long, and 4.5 inches in diameter. It had 70 tracks, 58 operational, and 12 spare. Each track held 1,728 bits. The drum held instructions, constants, target data, and timing tracks.

It was later replaced by the Delco Electronics Magic 352, a modified aircraft computer, as part of the Universal Space Guidance System. This system used inertial guidance, and star tracking. The MAGIC 352 had 4k of core memory, using 24 bit words. The cpu was implemented with Fairchild Micrologic integrated circuits. The computer weighed 35 pounds, and occupied a volume of a little over ½ cubic foot. Total power consumption was 90 watts. It had a 70 microsecond add, 258 microsecond multiply, and 398 microsecond divide.

Titan-III

The Titan-III is a heavy lift vehicle, still in use today. It can put 7,500 pounds in polar orbit. The ASC-15 flight computer for the Titan-III had a larger drum, with 20 more tracks. This allowed for the storage of 9,792 instructions and 1,152 constants, with a transfer rate of just under 175 kilobits per second. Add time was 156 microseconds, multiply time was 1,875, and division, 7,968. As the Titan-III was used as a space launch vehicle, it got a new computer, the Univac 1824. It was also based on the Athena, in the sense of having 24-bit words. It implemented 2's complement arithmetic, and had thin film memory Instructions were 16 bits, with a 5-bit opcode and 8-bit memory address, and a bit to indicate whether a base register was used in the effective address calculation. It had

three index registers. The first unit was delivered in 1968. The 1824, like its sister unit in the P-3 Orion aircraft, used Diode-Transistor Logic, in flatpacks.

The later Titan-IIIc delivered several Viking missions to Mars, and launched dual missions to Jupiter and Saturn in 1977. These spacecraft continued out of the solar system into interstellar space.

The 1824 Flight Computer was built in the 1960's by Sperry Rand UNIVAC, Defense Systems Division, a heritage company of Lockheed Martin. It was designed to perform on-board missile guidance and was selected as the guidance computer for the TITAN IIIC missile built by Martin Marietta Corp.

Titan-III

The Titan-III had optional solid boosters to increase weight to orbit. It used the same LR87 liquid engines as Titan-II models. It could use the Agena upper stage. The model with the solid booster was termed the Titan-IIIC. There were also -IIID and -IIIE models, used for planetary launches. The Titan-III used a guidance system from the A.C. Sparkplug Company, with an IBM ASC-15 computer, also used on the Titan-II.

Titan-IV

The Titan-IV was a stretched version of the -III, with solid boosters. If a second stage was desired, a Interim Upper Stage (IUS) or a Centaur could be used. Before the Saturn, the Titan-IV was the most powerful non-human rated vehicle in the United States. If you absolutely had to get to Saturn or beyond, the Titan-IV was your vehicle. It could hoist 21,680 kg to LEO.

A follow-on vehicle named the Titan-V was proposed, but not built. The Titans have been decommissioned, and some have been donated to museums.

Peaceful Launch Vehicles

This section discusses launch vehicle developed for peaceful purposes.

Saturn-I and Ib

The Saturn 1 was the first in a series of heavy lift rockets, leading to the Saturn-V. It could lift 9,000 kg to low Earth orbit (LEO) from launch complex LC-37 at the Kennedy Space Center in Florida. It was 180 feet long and 21.4 feet in diameter. The first flight was in October of 1961. The first stage Saturn booster used 8 clustered Redstones, with the Rocketdyne H-1 engine. The second stage, the S-IV, had six RL-10 engines, burning liquid hydrogen and liquid oxygen. A burn time of around 480 seconds could be achieved. Block–II vehicles were used in flights 6 through 10. The H-1 is directly traceable to the V-2. North American Aviation was given several V-2 engines, and converted them from metric to English measurements, to match U.S. Manufacturing capability. These original V-2 engines produced 59,600 lbf. A lot of documentation had also been captured, and some advanced design studies. One of these was the design of an improved fuel injector, which was implemented by North American. The H-1 engine was single-start. It could be fired multiple times on a test stand, but could only be used once in flight, since a non-reusable solid gas generator was used to start the turbopumps.

The Saturn-1 launch vehicle used a unique control computer built from discrete components, with 27-bit words. A magnetic drum of less than 100k words capacity, was used as memory. It was a simplex design, with no redundancy. It weighed under 100 pounds, and consumed 275 watts of power.

With the Instrument Unit, Apollo payload, and Launch Escape System (LES), the total vehicle configuration stood 57.3 meters tall, with a weight in excess of 513,000 kg. An Instrumentation Unit is at the Smithsonian's Udvar-Hazy Center. The IU is the guidance computer for the Saturn vehicle.

All ten launches of the Saturn-I models from 1961 to 1965 were successful. The follow-on to the Saturn-I was the Saturn-IB, and the follow-on to that was the larger Saturn-V vehicle, required to achieve a trans-lunar trajectory. The Saturn IB had 9 successful launches, including the post-Apollo Skylab and Apollo-Soyuz missions. Saturn-V rockets were used for the 13 lunar mission launches. There were no failures of the Saturn launch vehicles in any of their flights, a tribute to the engineering prowess and attention to detail of the von Braun team.

A Saturn-I vehicle can be see at Huntsville, and a 1B model is at Kennedy Space Center in Florida..

Saturn-V

The Saturn vehicles were developed by the von Braun team at Marshall Space Flight Center, formally the Army's Redstone Arsenal, in Huntsville, Alabama. Von Braun and his team of scientists and engineers had been brought to the U.S. by the Army after World War II ended. The rocket program was kicked off during the early post-World War-II Cold War era by President Eisenhower. At the time, the United States was in a race to space, and particularly, a launch vehicle race, with the Soviet Union. Each U. S. military service, the Army, Navy, and Air Force were developing their own rockets. Inter-service rivalry was finally squashed by Secretary of Defense Charles Wilson, who decided in November of 1956 to make the Air Force the primary missile developer for long range ballistic and space missions. The specifications for a heavy-lift vehicle were developed by the Advanced Research Projects Agency (ARPA). This would eventually become NASA's Saturn-V.

The Army found a loophole in Wilson's decision. His edict applied to weapons systems, so the Army Ballistic Missile Agency (ABMA), founded in 1956 at the Redstone Arsenal, decided to pursue non-military space launches. The only way to achieve the heavy lift required was to use a cluster of proven, off-the-shelf engines, from earlier vehicles like the Redstone and Jupiter. These rockets had also been developed by the von Braun team at ABMA. The "Super-Jupiter" (Saturn) solved the Stage-1, getting-off-the-ground, problem in an evolutionary fashion, building upon proven components, designs, and procedures. The Russians proceeded along the same path, using clustering techniques on their Soyuz launch vehicle, which was derived from an earlier military missile.

The formation of the National Aerospace Administration (NASA) in 1958 for pursuing peaceful civilian uses of space provided a framework to address the lunar mission, a high-visibility project to demonstrate the superiority of American technology to the world, kicked off by President Kennedy.

President Kennedy said the Saturn-I represented the first time the U. S. lift

capability to orbit exceeded that of the Soviets. He was assassinated in Dallas and did not get to see his project completed. The Saturn represented one of the first launch vehicles not to be designed specifically for military purposes. As a follow-on to the previous Jupiter rocket, and since Saturn is the next planet beyond Jupiter in the solar system, it got its name. There was no follow-on heavy lift vehicle beyond Saturn, as NASA chose to develop the mostly-reusable Space Transportation System (Shuttle).

The second stage of Saturn-I became the Saturn-V's third stage, and a new massive booster was developed for the first stage.

The Saturn-V was a three-stage, human-rated launch vehicle. Thirteen of the vehicles were launched, with never a loss of crew. Saturn-V models are on display at Marshall Space Flight Center in Huntsville, Alabama, the Johnson space Center, in Houston, Texas, and at the Kennedy Space Center in Florida. These are flight models, never used. All three stages used the same oxidizer, liquid oxygen (LOX). The first stage used RP-1 fuel, and the second and third stages used liquid hydrogen, LH2.

The vehicle stood some 363 feet tall, from the launch pad to the Apollo Capsule. It weighed a mere 6.5 million pounds, ready to launch. It could lift over a quarter of a million pounds to Earth orbit.

First stage - S1C

The first stage of the Saturn Rocket "stack" was the heavy lift stage, consisting of five Rocketdyne F-1 engines, one fixed in the middle, and four outside units that could swivel for steering and attitude adjustment. The first stage booster did not incorporate active guidance. The stage's job was to get the rocket and its payload from a standing start to 67 kilometers up, 93 kilometers downrange, and moving at 2,300 meters per second. That required 168 seconds of engine burn time. The total thrust developed by the engines was 7,600,000 pounds-force. Most of the first stage was fuel. The dry weight was about 130 tons, and the fueled weight was 2,300 tons. Any deviation of the vehicle during first stage burn was noted, and adjusted for during the second stage burn.

The engine's sequence of events was controlled by an onboard sequencer. This was not a computer, but just a fixed series of commands that were played out in time sequence. The center engine of the stage was started 8.9 seconds before launch, with pairs of outboard engines starting at 300

millisecond intervals. This technique was used to reduce structural loading on the rocket. When the computer in the Instrument Unit confirmed thrust level correctness, the pad hold-down arms released the rocket. In the Instrument Unit, the Saturn Emergency Detection System (EDS) inhibited engine shutdown for 30 seconds after launch. It was calculated that this was safer than having a shutdown early in the sequence, which would result in a non-survivable event for the astronauts.

The sequencing of events took place on a prearranged timeline. As the vehicle lifted past the tower, it was yawed 1.25 degrees away from the tower, to provide a margin of safety in high winds. Past 400 feet, a pitch program kicked in, having been adjusted for the expected winds that month. The vehicle also rolled to the correct flight azimuth. The outboard engines were tilted to the outside, so their thrust vectors went through the vehicles center of gravity. This was to minimize the effect of one outboard engine failing. At roughly 1 minute into the flight, the vehicle broke the sound barrier. Guidance adjustment was provided by the computer in the Instrument Unit (IU). The initial trajectory was designed to gain altitude quickly as the main goal. The engines; thrust grew from 7.5 million pounds-force at launch to over 9 million, in the thinner air at altitude. At the same time, the mass of the vehicle went down dramatically, as fuel and oxidizer was burned at the rate of 13 tons per second. The maximum acceleration was reached in over two minutes, at 4 G's. At this point, the center engine was shut down to limit acceleration, and the four outer engines used the remaining fuel and oxidizer. When oxidizer or fuel depletion was sensed at the pumps, the first stage was separated from the vehicle. Up high and moving fast, the first stage was separated to splash in the ocean, and the rest of the vehicle headed for Earth orbit.

Second stage - S-II

The second stage of the Saturn-V used the new J-2 rocket engines, burning liquid hydrogen and liquid oxygen. This stage was also almost completely fuel, weighing about 40 tons dry, and over 500 tons fueled. The engines developed over a million pounds-force in vacuum. The difference between the temperature of the propellant and the oxidizer was significant, around 70 degrees C. Thus, the liquid oxygen, being hotter, could boil the liquid hydrogen. This was prevented by extensive insulation.

After the first stage separation was confirmed, it was ignited by the

controller in the IU, and burned for about six minutes. By that time, the vehicle was 110 miles up, and nearly at orbital velocity. The second stage was actively controlled during power flight by the computer in the IU, using a path-adaptive guidance plan, that optimized propellant usage. Every two seconds, the actual state vector was compared to the expected. Commands could be issued by the digital computer to the analog flight controller computer (in the IU) to command gimbal angle changes in the nozzles, for steering control. The IU was also monitoring propellant levels in the S-II stage, and commanded engine shutdown and stage separation at the correct time.

About 38 seconds after second stage ignition, the vehicle control switched from a pre-programmed trajectory to closed loop control. The Instrument Unit now computed in real time the most fuel-efficient trajectory toward its target orbit. If the Instrument Unit failed, the crew could switch control of the Saturn to the Command Module's computer, take manual control, or abort the flight.

Third stage – S-IVB

This stage had a single J-2 engine using liquid hydrogen and oxygen, and weighed around 11 tons dry, 130 tons fueled. This engine was a derivative of the one used as the second stage of the earlier Saturn-1 vehicle. The new engine was re-startable once. This was used to get to Earth orbit, and then to enter the trans-lunar injection path to lunar orbit. Active guidance was provided by the Instrument Unit.

The Instrument Unit (IU) was the center point of the data flow on the Saturn vehicle, sending data both up and down the vehicle. It was introduced with the Saturn-I, Block–II, unit SA-5. It was designed at MSFC, and produced by IBM Corp. It used for vehicle guidance, control, and sequencing. The IU had its own telemetry, tracking, and power systems. The first model was a ring structure 154 inches in diameter, and 58 inches high. The large diameter matched the profile of the launch vehicle. Version two of the Instrument Unit was 34 inches high and 21 feet in diameter. It was constructed of an aluminum honeycomb, less than an inch thick, and weighed 2,670 pounds. It was unpressurized, unlike the previous version. Subsequent Saturn-V vehicles used a third version. The IU was placed between the S-IVB second stage and the Apollo spacecraft payload, and was an integral structural member. The IU was cooled by a

water/methanol heat exchanger, and powered by batteries.

In the Saturn-V configuration, the IU Launch Vehicle Digital Computer (LVDC) had 6 memory modules of 4096 28-bit words. The computer could achieve 9,600 fixed-point operations per second. An Add or Subtract operation took 82 microseconds, and Multiply and Divide, 328. Add/Subtract, and multiply/divide could take place simultaneously. There were twelve prioritized interrupts. All hardware was triplicated, for reliability. The computer had an associated Launch Vehicle Data Adapter, handling input and output. Besides attitude correction calculations, the digital computer handled sequencing of events, such as staging. Memory was based on ferrite cores.

In addition to the digital computer, the IU had an analog Flight Control Computer. The digital unit monitored status and calculated attitude corrections. The analog computer was used to command these corrections as angular adjustments for the swiveling nozzles.

The unit was powered by four 28-volt batteries. Heat generation in the unit was handled by a liquid cooling loop, which dumped heat to the outside air.

Before launch, a precision theodolite was used to align the inertial platform in the IU to the exact launch azimuth. The ST-124 inertial platform switched from an Earth Reference to a space-based frame of reference 5 seconds before liftoff.

The ST-124 3-degrees of freedom Inertial Platform Assembly, produced by Bendix Corporation, was a derivative of similar gyro-based platforms used on the German V-2 missile. It included three single degree of freedom precision gyros, and accelerometers. Active guidance was not required during the main boost phase, as the pre-programmed first stage's job was to just get the vehicle up and moving.

The IU included a data adapter to interface with the various sensors and other systems. This unit transformed the various formats, including analog, to a standard digital format the digital computer could use.

Before launch, the LVDC was connected to the ground control computer

via umbilical.

Control of the first stage was based only on a time sequence. True guidance was not applied until after the second stage burn had been initiated. Engine cut-off was determined by having achieved a velocity sufficient to enter Earth orbit. The algorithm was a minimum propellant flight path, using calculus of variations. For the second and subsequent stages, closed loop control was used.

When the IU sensed that the propellant level in the first stage had reached a preprogrammed value, it commanded stage cut-off and the separation sequence. It handled a similar role for the second stage. The IU controlled the first burn of the third stage, to achieve Earth orbit, and the second burn, to enter the trans-lunar trajectory. The IU had done its job at this point, about 6 ½ hours after launch.

Until a large enough aircraft became available, the IU was delivered from Huntsville to the Cape via barge. In one case, schedule pressure required construction of a portable clean room on the barge, and work on the IU was completed en route.

A flight spare IU can be seen at the National Air and Space Museum, Steven F. Udvar-Hazy Center, near Dulles Airport in Virginia.

The Apollo payload consisted of the Launch Escape System, the Apollo capsule, the service module, and the lunar lander. The launch escape system (LES) was located above the Apollo capsule and was jettisoned early in flight. The Lunar Excursion Module (LEM) was stored behind the service module. Once in Earth orbit, the capsule and Service Module were separated, the capsule rotated 180 degrees, and docked to the Lunar module. The lunar package was then separated from the third stage. The capsule, lander, and service module left Earth orbit heading for the moon, while the Third stage was commanded into a solar orbit, to get it out of the way.

The Command Module, or Apollo capsule, was the cockpit and living quarters for the three astronauts. The computing heart of the capsule was the unique Apollo Guidance Computer. The need for a computer onboard the Apollo was required by the chosen approach to the mission. Part of the spacecraft (Command and Service Modules) would remain in lunar orbit,

while a detachable part (LEM) would descend to the surface. Later, the LEM would return to lunar orbit and rendezvous with the Command Module, which would then leave lunar orbit and return to Earth. The ability of the Command Module and LEM to do in-flight computations was crucial to this approach. At the time, the only guidance computes were developed for ballistic missiles, and were buried in hardened bunkers.

The Service Module was located behind the Command Module, and the astronauts had no direct access to it. It was unpressurized, and contained a restartable liquid rocket engine and associated propellant, fuel cells, and electronics to support the mission. The fuel cells used hydrogen and oxygen, and some oxygen was also used to replenish the Command Module atmosphere. It had a reaction control system to adjust the spacecraft attitude. The service module had radiators to dump excess heat, and a high gain antenna to communicate with Earth. The Command Module stayed attached to the Service Module until just before reentry into the atmosphere, when the Service module was commanded to reenter the atmosphere independently and burn. The Service Module relied on the AGC in the Command Module for computation.

The Lunar Excursion Module (LEM) allowed a two man crew to land on the lunar surface, stay for a period of exploration, and return to the Apollo Command and Service Modules in lunar orbit. It had an Apollo Guidance Computer, programmed for the different and difficult tasks of landing on the lunar surface, and later taking off from the surface. Compared to the Launch complex at KSC with all its support infrastructure, the computer in the LEM did not have a lot to work with.

The LEM had two sections, one of which held the descent engine, and stayed behind on the Lunar Surface. The Ascent Stage, holding the two astronauts, rendezvoused with the Command and Service module in lunar orbit. The LEM was deliberately deorbited and crashed into the lunar surface, to facilitate seismometer readings for the lunar geologists. To this date, the LEM is the only crewed rocket vehicle to take off from a location not on Earth.

Saturn-V displays are located at Kennedy, Houston, and Marshall (U. S. Space & Rocket Center). In addition, Saturn-V first stage engines (F-1) can be seen at the Smithsonian National Air and Space Museum, Washington, DC; Kalamazoo Aviation History Museum (Air Zoo), Kalamazoo, MI; New Mexico Museum of Space History, Alamogordo,

NM; and Powerhouse Museum, Sydney, Australia.

Delta

The Delta is a civilian launch vehicle, using the Thor as a first stage. Later models use up to 8 Castor-IV solid strap-ons, which are ignited 4 at a time. I found they were good to lean against and take a nap while waiting for payload shroud access, at Vandenburg AFB.

Thor was the first operation ballistic missile by the U.S. Air Force. It was first launched in 1957, and in service from 1959 to 1960. About 225 were built. Like the Jupiter and Atlas, it used an engine design based on the Rocketdyne LR-79. Thor's left from Kennedy, and Vandenburg AFB on the West coast. It had a capacity to LEO of 1,270 pounds. Thor was active from 1957 through 1980.

Delta was a NASA vehicle, built by McDonnell Douglas, designed specifically for access to Space, not as a ballistic missile. First launch was in 1960, and the rocket is still in use. The Delta vehicle uses a Delco guidance computer. The original model (1960-1989) had a capacity to LEO of 3,800 kg. It came in 17 variants.

The Delta vehicle made 99 successful launches, and there was great anticipation about the 100th. Let me not keep you guessing – it blew up. A Delta can be seen at the Goddard Space Flight Center's Visitor Center.

Delta II had a capacity to LEO of 6,000 kilograms, and was built by ULA Notably, it was used for a pair of Mars probes, Delta-iii was a Boeing product, with a LEO capacity of 8,200 kg. It was used from 1998-2000. Delta-IV is in use from 2002, and can place a payload of 23,000 kg in LEO.

United Launch Alliance is deploying a new vehicle, using the Delta IV fuselage, and up to six solid rocket booster strap-ons. A planned upgrade would allow recovery of the engines to reduce the launch cost. The upper stage would use the Centaur. An advanced cyrogenic upper stage is also envisioned.

Delta IV Heavy has been in use since 2004. It has a payload to LEO

capability of 63,450 kg.

Vulcan

The Vulcan vehicle is under development by the United Launch Alliance. It will have a capability of 40,000 kg to LEO. First launch will be around 2019.

It features a new first stage, developed in partnership with Blue Origin. It uses liquid methane and liquid oxygen. The BE-4 engine will replace the currently used RD-180, from Ukraine. Solid booster strap-ons can be used. In addition, upper stages can be used.

They are investigating making the engines re-usable, by having them separate from the tanks, and parachute down, to be captured by a helicopter.

Space Launch System

The Space Launch System (SLS) is a derivative and re-purposing of the ARES system, which only flew once before program cancellation.

The Ares rockets were a family of three launch vehicles derived from the Shuttle. Ares-1 was human-rated, and had a capacity of more than 25,000 kg to LEO. The Orion capsule was retained, but the launch vehicle was changed. The European Space Agency will develop the service module. The old Apollo/Shuttle launch support systems at KSC were upgraded to support SLS.

The SLS is being developed to support crewed lunar and Mars missions. A lot of the technology has its origins in the Shuttle program. The Ares IV and V designed were combined into a single vehicle for crewed and cargo use. It will have a total thrust greater than the Saturn-V.

The SLS will be an evolving design. The first model, Block 1, can lift 70 metric tons to Earth orbit. Block -2 will use advanced engines to be able to push 130 metric tons to LEO. (The Saturn-V could lift 140 tons to LEO. It will be capable of crewed lunar missions. Further enhanced Block 2

models will be used in the crewed Mars mission. The SLS will be used with the Orion capsule and service modules, and can be used to support the International Space Station. It will launch from Launch Complex 39B at KSC. Modifications to the pad, the flame trench, and the mobile launch platform are required.

The SLS has a center core stage with four liquid fuel engines, and two solid fuel boosters. The liquid fuel engines will initially be RD-25D's surplus from the Shuttle program. These engines were designed to be reusable. Single use, cheaper engines are in development for the SLS. The main body of the first stage will be a modified version of the shuttle's external tank. Above that will be an inter-stage.

The first two models of the SLS will use 5-segment solid rocket boosters, derived form the 4-segment models of the Shuttle system. There are currently no plans to recover and reuse the solid booster casings. Block 2 models of the SLS will use new advanced solid boosters. The liquid fuel and oxydizer tanks will be derived from the shuttle external tank design. A modification will allow a second stage above the tank. It will all be built at NASA's Michoud Assembly plant, and delivered to the launch facility by barge.

The second stage will be the Interim Cyrogenic Propulsion stage, using a single RL10B-2engine burning liquid hydrogen and liquid oxygen. This will be a modified version of the one used on the Delta IV. This stage will be able to send a payload into a circumlunar injection trajectory.

The Exploration Upper Stage will have four liquid fuel RL-10 engines, and fill the role previously done by the Saturn V 3rd stage.

Sounding Rockets

Sounding rockets are not intended to go to orbit, but just high into the atmosphere. The science payload is generally parachuted back to Earth. Sounding rockets don't have the duration of balloons, but can usually carry heavier payloads to a higher altitude. Sounding rockets can also be launched from platforms and ships at sea.

A sounding rocket is a instrument-carrying research vehicle launched on a sub-orbital flight. It is up and back, not going to orbit. Missions are

generally in the range of 50-1,500 km, the lower levels also being the domain of balloon-borne payloads. Actually, a sounding rocket can be launched from a balloon, a combined device called a “blooster.” Sounding rockets can be solid or liquid fueled, and can be single or multi-stage.

Sounding rockets are generally smaller than their orbital counterparts, and less complex to launch, thus, cheaper. They usually have a solid rocket motor. There are numerous sounding rocket launch sites around the world, and they can also be transported by helicopter to remote locations for a launch.

U. S. Sounding rockets include the Astrobee, the Aerobee, and a series of Nike- and Terrier-based rockets. The Loki family is based on an unguided anti-aircraft missile, itself based on a German World War-II anti-aircraft rocket called the Taifun. Neither of the war missiles saw service.

The Canadian Black Brant has gone through 12 models. The latest model is a 4-stage vehicle, with 1st and 2nd stages derived from the Talos and Terrier missiles. It can handle a payload of over 400 kg, to an altitude of 1500 km.

The Australian Kookaburra is a two stage vehicle, launched from Woomera, and an atoll in the Indian Ocean.

Space Shuttles

The Space Transportation System (STS) was a crewed launch and recovery system for spacecraft, that used rocket propulsion to achieve orbit, and glided back to Earth to land on a run-way. A major advantage of the Shuttle system was, when it carried a spacecraft to orbit, it could check to see if it survived the harsh launch environment. If not, the Shuttle could bring it back. Perhaps its major achievement was to repair the Hubble Space Telescope in orbit over several missions. The Shuttle was instrumental in assembling the International Space Station.

The Shuttle was similar in size to a DC-9 jetliner, and was of a lifting-body design, going back to the German *Silbervogel* design of World War-II. The entire lower surface of the craft acted as a wing. At launch, the STS consisted of the winged Shuttle vehicle, a large liquid fuel and oxidizer external tank, and two solid rocket boosters. The solid rocket

casings were retrieved from the ocean, and refurbished and reused. The external tanks were not recovered, and were targeted away from shipping lanes in the Pacific and Indian oceans.

There was a mockup, a prototype, and five flight units of the shuttle. Two of the flight units were destroyed, one at launch, one at reentry, with loss of crew.

You probably won't get to go inside, but if you enter the hatch, you are on the lower deck, and the toilet is just to your right. Climb the ladder to the flight deck. In orbit, the cargo bay doors are open, to expose large radiators to space, for cooling purposes. The “arm” is controlled from the back of the upper deck, with windows for visibility.

The Shuttle Orbiter had three engines, fed from the large external tank. When the engines had burned sufficiently to achieve orbit, the Orbiter separated from the tank. The Orbiter continued to its destination altitude. The engines went with it, but no longer had a source of fuel or oxidizer. The Orbiter could adjust its orbit somewhat with its OMS (orbital maneuvering system) engines, using fuel onboard. There were also (reaction control system) RCS engines to adjust attitude. Upon reentry, the Shuttle flew in a nose-up attitude, as the bottom of the craft and wings were covered in heat-resistant tiles. After sufficient atmosphere was reached, the aircraft control surfaces could be used, and the Orbiter was flown like a plane to a runway landing. Well, like a 165,000 lb glider. No air-breathing engines were included. These were considered and rejected in the early design phase. They would have allowed the Shuttle to maneuver in the atmosphere and extend its range, at the cost of complexity and weight.

Ideally, the Orbiter landed at the runway back at the Launch site, and could be easily towed to the maintenance facility. Another option was to use the Dryden Flight Facility's vast expanses of hard desert. In that case, the Shuttle was brought back to the Kennedy Space Center on the back of a specially modified 747 carrier aircraft.

There was a plan to launch Shuttles from Vandenberg Air Force Base in California, which would allow them to go to polar orbit. This was not implemented. There was also a two stage rocket called the Interim Upper

Stage or Inertial Upper Stage (IUS) which would deploy from the Shuttle bay with a payload going to a higher orbit. One mission carried the Ulysses spacecraft to study the polar regions of the Sun. Quite a few were used to put the Tracking and Data Relay Satellites (TDRS) into orbit.

A versatile craft, the Shuttle could take satellites to orbit, check them out, release them if they worked fine or bring them back, if they didn't. The Shuttles also made several repair trips to the Hubble Space Telescope, to work around its optical problem, and change out some failed computer and such. The shuttle carried up to 8 crew, some upstairs, some on the lower deck (cheap seats, no view), and could accommodate 11 in an emergency.

NASA re-purposed the Apollo Vertical Assembly Building (VAB) at the Cape to assemble the Shuttle stack. The solid boosters were bolted down on the crawler/transporter base, and the large external tank and Shuttle Orbiter were hoisted up and attached. This facility has such a massive volume inside, it has its own weather, There are two launch pads, 39-A and 39-B, essentially identical.

The launch sequence proceeded in a well defined procedure. The three liquid engines were ignited one at a time in sequence, to check that they were all working properly. This pushed the orbiter's nose forward about a meter. When the liquid engine performance was verified, the explosive bolts holding the solid boosters to the pad were blown, and the solid boosters were ignited. Then, you were on your way.

In video's of a Shuttle launch, you will see a series of sparks below the engines. That was to ignite any residual or leaked hydrogen from the external tank. A huge water spray was started before engine ignition. This was to partially protect the pad, but also to damp the acoustic energy from the engines. Otherwise it reflected up onto the vehicle, and could do damage to the engines.

The Space Shuttles carried five identical computers, the circa-1972 AP-101's, derived from the IBM System/360 System/4 Pi mainframe architecture. It was a 32-bit machine with 16 registers, and was microprogrammed. It had an instruction set of 154 opcodes. One of the five AP-101's on the Shuttle contained software derived independently from the software loaded on the other four. Each unit had a CPU and an

IOP - Input/Output Processor. Each IOP had 24 channels, each with its own bus and processor. Triple redundant power supplies, fed by separate essential electrical buses were used. The computers were located in three separate locations in the Shuttle Orbiter. Redundancy is everything.

When the Space Shuttle was introduced, it was designed with two re-usable solid rocket boosters, that would drop into the ocean and be recovered by ships. They would then be returned to Cap Kennedy for refurbishment. The ships were the *MV Liberty Star* and *MV Freedom Star.* Each ship handled one booster. There was a 7,500 pound capacity deck crane to lift the end of the booster onboard. These vessels were also employed to tow the barge with the Shuttle's external fuel tank from the assembly plant at Michoud, LA, to the Cape. The boosters were separated from the Shuttle at T plus 2 minutes, 7 seconds, having done their job of getting the vehicle up high and going fast. Parachutes deployed, slowing the 165,000 booster casings to 62 mph.

There was an modular “Upper stage” developed for the Shuttle, since that vehicle could only go to low Earth orbit. This was called the Payload Assist Module, or PAM. It was also used for the Delta and Titan, and was capable of putting satellites into geosynchronous orbit. It was a McDonnell-Douglas design, using Thiokol solid fuel motors. PAM-D for the Delta rocket is still in use.

It is interesting to look at satellite deployment from the Shuttle as opposed to deployment from an expendable booster. The launch and ascent is the worst environment, with vibration and acoustics. In the case of the Shuttle, once on orbit, the satellite could be turned on and tested, and returned to Earth if necessary. The flip side is, every payload on the Shuttle had to be “human-rated,” a higher level of certification.

Pathfinder, a full-size mock-up, is at the Alabama Space and Rocket Center, Huntsville, AL. OV-101 *Enterprise*, a prototype used for flight tests in the atmosphere, is at the Intrepid Sea, Air & Space Museum in New York City. OV-102 *Columbia* was destroyed (with loss of crew) in a re-entry accident on February 1, 2003. OV-099 *Challenger* was *d*estroyed (with loss of crew) in a launch accident, January 28, 1986. Debris was recovered and is stored, sealed in an old missile silo, at Cape Canaveral Air Station, FL. OV-103 *Discovery* rests in the National Air and Space

Museum, Steven F. Udvar-Hazy Center, Chantilly, VA. (near Dulles Airport). OV-104 *Atlantis* may be see at the Kennedy Space Center, Cape Canaveral, FL. OV-105 Endeavor is at the Samuel Oschin Pavilion of the California Science Center in Los Angeles, CA.

No flown external tanks have survived, but unused ET-94 is in Los Angeles and will be on display with Space Shuttle Endeavor at the California Science Center, when the Samuel Oschin Air and Space Center opens in 2018. Three external tanks were in manufacturing when the Shuttle Program ended, numbers ET-139-141.

Sounding rockets

Sounding rockets are not intended to go to orbit, but just high in the atmosphere. The science payload is generally parachuted back to Earth. Sounding rockets don't have the duration of balloons, but can usually carry heavier payloads to a higher altitude. They are used to launch payloads that take measurements of ambient conditions at altitude where balloons can't reach, and is too low for satellites, between 40-120 km.

Sounding rockets have the advantage of being able to be launched almost anywhere, including form the deck of a ship. A lot of them are based on surplus military rocket systems. In the US, this includes sounding rockets based on the Nike booster. Sounding rockets generally us the easier to handle solid fuel engine. They can include several stages. They are lower cost than a satellite. They are used for atmospheric studies, ultraviolet and x-ray astronomy, and microgravity research.

Sounding rockets have been used since before the first satellite made it to orbit. May countries around the globe have fixed sounding rocket launch sites. These include Norway, Sweden, Japan, India, Australia, New Zealand, Iran, Indonesia, and Brazil, among others.

The U.S. Scout entered service in 1960, and was used until 1994. It could put 200 kg in LEO.

Soviet/Russian

This section discusses the Soviet, and later Russian, rocketry efforts. As with the United States, the Soviet's early efforts were aided by the

Germany World War-II V-2 rocket.

Vostok A-1/SL-3

Vostok refers to a family of rocket vehicles, based on a ICBM design. Rockets from this series launched the first artificial satellite of the Earth, and the first human into space. The Vostok is a three-stage design. The 8K72K model, now retired, had a capacity to LEO of over 4,700 kg. The first stage consists of four liquid fuel strap-on boosters, The "second" stage consists of the core stage, the center engine that the boosters are attached to. A third stage places the payload into the correct orbit. They all use Kerosene and LOX.

Proton

The UR-500 Proton vehicle dates from 1965. It is a heavy lift vehicle, with a capacity of 22.8 metric tons to Low Earth orbit, 6.3 tons to Geostationary transfer orbit. It was originally designed as an ICBM (like the American Titan and Atlas), but was actually oversized for that role.

Dnepr

The Dnepr was developed and built in the Ukraine, in conjunction with Russia. It first launched in 1999, and was retired in 2015. It had a launch capability of 3,600 kg to LEO.

Energia

The Energia vehicle was a product of the Soviet Union. It was used from 1987-1988. It had a capacity to LEO of 100,000 kg, and was the launch vehicle for the Russian Buran Shuttle.

Zenit

Zenit is the name of a family of medium lift launch vehicles designed in the Ukraine in the 1980's, when that country was part of the Soviet Union.

It used liquid propellant. It was used as a strap-on booster for the Energia (4 units), and as middle weight launch vehicle for the Soyuz, or anything in the range of 7-20 (metric) tons. It was supposed to replace the R-7 and Proton. It was scheduled to take over the responsibility of crewed launches, but that got caught up in the Soviet Union collapse.

There are several variations. The Zenit-3SL is a three stage vehicle, specially built for SeaLaunch. Zenit-2 is a two stage vehicle launched from Baikonur's LC-45. It uses a single RD-171 engine, burning RP-1, and LOX as the first stage, and a RD-120 engine on the second stage. First flight was in 1985.

A Zenit-2 has a payload lift capacity of 13,750 kg to LEO. Zenit-3SL can get 1850 kg to GEO.

The Angara series are used for launch to LEO, with a payload of 3,899 kg.

The R-12 and R-14 Kosmos can lift 1,500 kg to LEO, and operated from 1967 through 2010.

N-1

The NPO Energeria N-1 has a capacity of 90,000 kg to LEO. It was used from 1969 to 1972.

R-7 Semyorka Soyuz

This rocket from RSC Energia can hoist 8,200 kg to LEO, and has been used for various Soyuz crewed launches.

China

The Chinese space program got kicked off before the 900's with *Arrows of Flaming Fire* being used in warfare. These were solid propellant, using gun powder, and stabilized by a long stick. They were mostly effectual due to their surprise and terror effect. They were adopted by the Mongols, and taken to the Middle East. No mention of the use of rockets in the Crusades could be found.

The Long March launch vehicle was introduced in 1970, and retired in 2002. It had a capacity of 750 kg to LEO. The follow-on models, -2, 3, and -4 could take 12,000 kg to LEO. The Long March-5, active from 2016, has a capacity to LEO of 25,000 kg. The Long March-6 has a capacity of 1,500 kg. The -7 model will do 30,000 kg.

China's LM3b

China is getting into the Private Space area, as of this writing, with OneSpace. This uses a solid booster, and is not reusable. It can lift 220 pounds to orbit, addressing the smallsat market.

India

India had a thriving rocket industry, probably developed from the Chinese fireworks. British Troop faced rocket artillery in India in 1780, and developed their own war rockets from these models. At the siege of Fort McHenry in the war of 1812, the phrase “rockets red glare” made it into the U.S. National anthem. (spoiler alert: we won).

The Indian government developed a series of launch vehicles to address the task of getting payloads to high and low orbits.

The Indian Space Research Organization developed the Geosynchronous Satellite Launch Vehicle-I and II. These have seen 10 launches, starting in 2001. Components from previous models were used, including solid rocket boosters, a liquid fuel engine, and a cyrogenic engine. It can supply 5,000 kg to LEO. The Mark-III (2014) vehicle gets 10,000 kg to LEO.

The latest model can place 4,000 kg in geostationary orbit, or 5,000 kg in low Earth orbit. Initial flights were made with Russian cyrogenic engines, as India developed this technology in-house. The 3-stage vehicle is 49 meters high, with a mass of 415 tons. The Indian CE-7.5 cyrogenic engine has replaced the Russian engines.

The ASLV, Augmented Satellite Launch Vehicle, was a 5-stage launch vehicle, with strap-on boosters, using solid fuel. It made 4 launches.

The PSLV, Polar Satellite Launch Vehicle, entered service in 1993, and can place a payload of 3,800 kg into LEO. It was used for the Indian Moon Mission, and the Mars Mission.

The Indian Space program is currently the third visitor to the Moon (2008) and Mars (2013), in the league of the United States and Russia.

Japan

The Epsilon launch vehicle has a capacity to LEO of 1,200 kg. It was introduced in 2013, and is currently active. The Mitsubishi H-1 was introduced in 1968, and retired in 1992. It had a capacity of 3,200 kg to LEO. The H—II, -IIA, and -IIB could handle 19,000 kg to LEO.

The J-1, from IHI Corp, a part of Nissan, gets 880 kg to LEO. It is currently retired. The Lambda-S operated until 1970.

The N-1 and N-2 could place 2,000 kg in LEO. They were used from 1975 to 1987.

South Korea

The Naro launch vehicle operated from 2009 to 2013, with a capacity of 100 kg.

Brazil

The Veículo Lançador de Satélites (VLS) was a Brazilian developed launch vehicle. Development began in 1984. The first two versions were dual stage, with later models being 3-stage. Previously, Brazil developed a series of sounding rockets, the Sonda vehicles. These are launched from the Alcântara Launch Center. This is the closest launch center to the equator. It is claimed to have a 35% fuel savings over launches from KSC.

The Brazilian Space Agency was created in 1994, under civilian control of the Ministry of Science and Technology. Previously, the launch vehicles had been under the control of the military.

Europe

Aerospatiale provides Ariane launch vehicles to ESA, the European Space Agency. The first three models, now obsolete, could lift 2,650 kg to GEO. The fourth model, also retired could do 4,725 kg to GEO. Ariane-5 is in current use, sending 21,000 kg to LEO, or 10,750 kg to GEO. The Ariane-

6 is in development, with a projected payload to LEO of 20,000 kg.

France developed the Diamnat vehicle in 1965. there were a total of 12 launches, and it is now retired. French space efforts are now under the ESA umbrella.

Other Countries

Other countries around the globe have developed satellites and launch vehicles on their own or with the help of the early space-faring nations. I have chosen not to include all these program, leaving them for another book, as the numbers are large. This book will focus on the major players in space. As we will see next, these have gone beyond government efforts into the private domain.

Commercial Efforts

This section will discuss rockets developed by the evolving commercial spaceflight industry.

Orbital ATK

Orbital ATK was formed in 2015 by the merger of orbital Sciences Corporation and the defense and aerospace divisions Alliant Tech Systems.

Pegasus

The Pegasus has been used since 1960, and has a capacity of 450 kg to LEO. It is an air launched and uses solid fuel engines. It can place 440 kg to LEO. It was first used in 1990, and is still in service. The vehicle's wing was designed by noted aviation pioneer Burt Rutan. The first launch was from a Military B-52, but Orbital has since used a converted L-1011. These can use the runways at KSC, Vandenburg, the Dryden Flight Research Center in California, or the Wallops Flight Facility in Virginia. Most large airports could support the launch, giving a large range of flexibility to orbital inclination.

Minotaur

The Minotaur-I was derived from the Minuteman-II missile, and has a capacity of 575 kg to LEO. The Minotaur -IV and -V have a capacity of 1,750 kg, and are active since 2005. They launch from Vandenburg or Wallops.

Antares

The Antares vehicle is a two or three stage expendable launch vehicle. It was originally called the Taurus II, and can put 6,500 kg to LEO. It first lunched in 2013. It uses the Mid-Atlantic Regional Spaceport on the Virginia coast as a launch site for the Antares Commercial Resupply Services launches to the International Space Station.

The first stage uses RP-1 and LOX as propellant and oxydizer. This stage was designed and manufactured in Ukraine. It is similar to the Zenit vehicle. The second stage is solid fueled, based on the Minotaur's first stage. There are options for the third stage. It can use nitrogen tetroxide and hydrazine, or a solid engine.

NGL/Omega

The Next Generation Launcher Project will use to the maximum extent existing facilities at KSC, and possibly Vandenburg AFB. It is to be launched from Pad 39B, and share infrastructure and services with the SLS. The official name of the vehicle is Omega. It will use the RL-10 engine. There will be a four-segment solid booster, NS cyrogenic upper stage. Various options are available to meet weight requirements. It can put up to 10,000 kg to LEO.

Blue Origin

Blue Origin's uses its own engines, the BE-4 which burn LOX and methane. The booster from the test flight was recovered and will be reused. New Glenn is a launch vehicle in development by the company, It will have 2 or 3 stages. The first stage uses 7 of their BE-4 methane/oxygen engines. The second stage uses one of these engines, with a different nozzle, optimized for the less dense atmosphere at altitude. New Glenn is a follow-on to their earlier New Sheppard vehicle. It will have a capacity of 45,000 kg to LEO.

The vehicle is 7 meters in diameter. The first stage lands vertically after separation, and is intended to be used 100 times. The two stage vehicle has a capacity of 13,000 kg to geosynchronous transfer orbit, and 45,000 kg to low Earth orbit. The Blue Origin vehicles uses the Launch Complex 36 at the Kennedy Space Center, under lease from Spaceport Florida. This was the old Atlas launch facility.

Strato Launch Systems

Stratolaunch Systems, of Seattle, owned by Paul Allen, are developed their own air launch to orbit system. This uses a carrier aircraft from Scaled composites, and a multi-stage vehicle launched from high altitude to orbit. The carrier aircraft, represents the first stage, and can be re-used. It will include 6 Pratt & Whitney PW-400 air breathing engines. It has not yet flown, as of this writing. It will be the aircraft with the longest wingspan to fly. The upper stage might be the Orbital ATK Pegasus-II with a solid engine. A liquid engine from Aerojet-Rocketdyne was also being considered. Stratolaunch pursued development of it own engine, and asked NASA for test services on the engine at the Stennis Space Center. The aircraft tested successfully at the Mojave Spaceport.

The untimely death of Paul Allen in October of 2018 lead to some changes at Stratolaunch. Operations were scaled back, and new development was put aside. The big launch aircraft is operational, but will not be used to launch spacecraft to orbit, as of this writing.

Scaled Composites/Virgin Galactic

Scaled Composites, owned by Virgin Galactic, developed a air-launched vehicle, for access to space for tourists. The carrier vehicle, White Knight Two, carries the smaller SpaceShipTwo to a high altitude,. At this point the two vehicles separate, and the White Knight fly's back to a runway landing as the smaller craft continues to orbit with its rocket engine. The two vehicles were designed and built by aviation and space pioneer Burt Rutan. The plan is to have five SpaceShip-2's, the orbital vehicle, and two WhiteKnight-2's, the crewed carrier vehicle. Two SpaceShip-2's are under construction, and there is one White Knight-2.

The White Knight, sometimes called a Flying Space Aircraft Carrier, carry's a flight crew of two. It's cargo capacity is 37,000 lbs to 50,000 feet. If it carries an “upper stage”, the Launcher One, it can put 200 kilograms to low Earth Orbit. White Knight has four Pratt & Whitney turbofan engines. The wingspan is 41 feet, and there are dual fuselages. The second fuselage can hold additional crew members, or tourists.

Sierra Nevada supplied the rocket motors for Virgin Galactic's Spaceship Two, and for Scaled Composites' Spaceship 1 and 2. This company was founded by famed aircraft designer Burt Rutan, and currently owned by Northrop Grumman. It is located at the Mojave Spaceport in California. The company is known for its unconventional designs, and use of advanced composite materials. It was granted the world's first license for a sub-orbital manned rocket flight.

Spaceship one (Scaled Composites model 316) is an air-launched rocket powered aircraft. It made its maiden flight on the 100th anniversary of the Wright Brother's flight. It carries a pilot and two crew or passengers. It has a reaction control systems for attitude control outside the atmosphere, as well as standard aerodynamic control surfaces. The wings can be tilted forward to form a shuttlecock configuration, useful in the early stages of reentry. The craft cannot take off on its own, and is carried to altitude by the White Knight mothership.

The craft uses a hybrid rocket engine from SpaceDev, with a solid, rubber-like propellant, and nitrous oxide. The engine can be shut down after it is started, but it is not throttleable. It has a total burn time of around 80 seconds. The craft is 28 feet long, with a wing span of 16 feet, 5 inches. It's empty weight is 2400 pounds. SpaceShipOne has flown multiple times.

SpaceShip Two (Model 339) is a larger model, holding 8 crew and passengers in total. It uses a larger rocket model, and the same feathered or shuttlecock stabilization for atmospheric reentry. It is roughly twice the size of its predecessor. In a tragic accident, the first model broke up in flight, and crashed into the desert, killing the pilot. A second unit has been constructed.

LauncherOne is a two stage vehicle under development, It will use a carrier aircraft as the first stage. It has a capacity of 300 kg to orbit. It is a

two-stage liquid-engined vehicle. It will use the Mojave Air and Space Port, with the services of Virgin Galactic's *Cosmic Gir*l 747. Actually, almost any airfield on the planet would work, if permission can be obtained. First launch is imminent, as of this writing.

Space Services Inc.

This Houston Company used surplus solid-fueled Minuteman ICBM's. It only launched three times, with two failures. There were six variations, of 4 to 5 stages.

Space-X

The Falcon-1 from Space-X had a capacity of 420 kg to LEO. It was in use from 2006-2009.

The Space-X Falcon 9 vehicle launched the USAF's X-37 Orbital Test Vehicle in September of 2017. It has a capacity of over 22,000 kg to LEO. It was launched the Dragon capsule, and is currently in use. Falcon-Heavy has a capacity of nearly 64,000 kg to LEO. It has twice the payload capability of the Delta IV heavy, at one-third the cost, according to the company. Each core is the equivalent of a Falcon-9. The first stage has three Falcon-9, nine-engine cores. Together the twenty-seven engines generate 5 million pounds-thrust at lift-off. That's nearing the capacity of the Saturn-V. Falcon-V will be crew-rated, with the Dragon capsule.

The second stage uses a Space-X Merlin engine. It is capable of multiple restarts, as required.

The Falcon heavy is a follow-on vehicle with the capacity of 44,600 kg to LEO. It was introduced in 2018, and is partially reusable.

The ITS is the Interplanetary Transport System by Space-X. It will enable the exploration and colonization of Mars. It was previously known as the Mars Colonial Transporter. It is a re-usable heavy lift booster. It uses Liquid Oxygen – Liquid Methane engines, and the point is not lost that those liquids could be manufactured from natural resources on the Moon and Mars. It will outperform the Saturn-V in lift by more than a factor of

three.

The BFR is in development, and may emerge by 2020. It will have a payload to LEO of 150,000 kg in its reusable configuration; 250,000 kg in the expendable version. It will have 42 of the Space-X Raptor engines. The payload mass to the surface of Mars is 450 metric tons.

Rocket Lab

Rocket Lab is an American company with a launch site in New Zealand. It is focusing on services to Cubesats. They had their first flight in 2017. Payload to a sun-synchronous orbit (500km) is 150-225 kg. Launch costs are around $6 million, for their Electron vehicle. They are cleared for a launch every 72 hours for 30 years. They also have a suborbital sounding rocket, the Atea-1 (which is Maori for *space*). It has a 2 kilogram cargo capacity. A sun-synchronous orbit is a special type of polar orbit where the satellite passes over a given point on the primary's surface at the same solar time. This has advantages in observation.

The rocket engine, the *Rutherford*, was designed in New Zealand, and produced in the United States. It uses RP-1 and Lox. It has a unique feature, it uses electric pumps, not turbo pumps. It is used on both the first and second stages. Most of it is 3D printed. The pump motors generate 50 hp at 40,000 rpm, using a lithium polymer battery. The motor generates a thrust of 162 kN at sea level.

They have a launch agreement in place with NASA. They launch from Great Mercury Island on the east coast of the North Island.

Alternatives

This section discusses alternatives to rocket power for launching payloads.

Single Stage to Orbit

Although multi-staged launch vehicles are the norm, a McDonnell-Douglas reusable single stage to orbit vehicle was initially a DoD Project, later transferred to NASA. It was termed Delta Clipper-Experimental DC-

X, later DC-XA. The idea was from prolific science writer Jerry Pournelle, who says the concept was conceived in his living room. It was partially based on a 1965 paper by Max Hunter. (see web address in “Resources”). It flew eight times, and the follow-on DC-A flew four times. A lack of interest by Industry, and a lack of funds killed the projects.

Air breathing winged first stage

The first stage can be a winged aircraft that takes off an lands from a conventional airport. This approach was used with Orbital Sciences Pegasus. It was also used with the X-15 rocket plane, as well as the Virgin Galactic Launcher1. We include the X-15 and its B-52 carrier here since the X-15 did go beyond the Kaman line, reaching space, as defined by the IAU.

Pegasus

The ATK-Pegasus vehicle uses a Lockheed L-1011 Stargazer aircraft as a first stage, releasing the rocket at around 40,000 feet. Pegasus flew in 1990. It has three solid propellant stages, with the option of a fourth. It has a Rutan-designed wing. The fourth stage has a re-startable liquid engine, using hydrazine.

Pegasus weighs around 18,500 kg, with the advanced Pegasus XL being in excess of 23,000 kg. The solid rockets were developed by Hercules Aerospace (currently, Alliant TechSystems). The payload capacity is 440 kg. Great flexibility of launch location is provided by the carrier aircraft.

Skylon

Skylon is a single stage to orbit spaceplane using a hybrid air-breathing rocket engine, with hydrogen for fuel. It is sized for 37,000 pounds of cargo to low Earth orbit. Design goals call for 2-day turn-around, and a 200 flight life. The plane may be ready for operation in 2025. It is based on the previous HOTOL Concept from the 1980's.

The hybrid engine would burn hydrogen, using atmospheric oxygen until reaching around 26 kilometers, where it would switch to the internal liquid oxygen. The engine is referred to as *Sabre*, Synergetic Air-Breathing Rocket Engine. It has been in development for over two decades.

It will have retractable undercarriage, like the Shuttle. The plane is to be about 83 meters long with a wing span of 26.8 meters. It can be configured to hold 24 passengers in the Skylon Personnel Logistics Module. The plane would normally not have a Captain or Pilot, but would be flown from the ground.

The project is being conducted by the U.K. Company REL (Reaction Engines, Ltd.). The intent is to operate for-profit, since the Skylon has the potential to lower launch costs. However, they estimate that $12 Billion will be needed to develop an operational vehicle. The European Space Agency and the British Government are contributing funds. Commercial entity BAE Systems has acquired a 20% share of the company.

Balloon launch

Stratollite Flight Services uses a high altitude balloon system that has a duration of months. It can also recover the instrumentation package after the mission is completed. Fifty flights have already been completed. The system can reach 46 km, not quite the limit of space, and handle a payload of 4,500 kg.

Space Elevator

The space elevator is a concept that would work nicely on the moon. It has the advantage of a lower gravity than Earth, no atmosphere, and it could be built with currently available materials. There is nothing nearby to interfere with its operation. The lunar elevator would span about 50,000 km. The elevator needs a solid tether on the surface, a large mass at the upper end, for a tether, and a very strong cable. A lunar elevator could be tethered to a mass at the L1 Lagrange point, between the moon and the Earth. An elevator on the back side of the moon is also feasible. Space elevators have been explored since the 1890's. We now have the technology to construct them. A handy asteroid could be used as the counterweight for the lunar elevator.

Mass Driver

A Mass driver is feasible on planets or moons without an appreciable atmosphere. It is an electromagnetic catapult, utilizing a long, linear motor. This works well on the lunar surface, with its reduced gravity compared to Earth, and lack of atmospheric drag. The other advantage is 15 days of sunlight, to operate the driver as well as charge batteries. In a mass driver, the payload does not contact the launch rail, but it magnetically levitated.

Afterword

There are many ways to get off the surface of a primary, and they are getting cheaper all the time. We might see this as a analog of the sailing vessels that could cross oceans in the Age of Discovery. Without that technology, “civilization” would have stayed in Europe. Sure, they were expensive for their day, and somewhat unsafe, but they opened up a new world for the European civilizations. Cheaper access to space is an enabling technology to open up new worlds and new sources of materials. Who knows what we will find?

Bibliography

Baker, David *NASA Space Shuttle Manual: An Insight into the Design, Construction and Operation of the NASA Space Shuttle*, Zenith Press, 2011, ISBN-0760340765.

Barber, Murray, *V2: The A4 Rocket from Peenemunde to Redstone*, 2017, ISBN-1906537534.

Bergaust, Erik, *Werner von Braun*, National Space Institute, 1976, ISBN-0917680014.

Bilstein, Robert E. *Stages to Saturn, A Technological History of the Apollo/Saturn Launch Vehicles*, 2003 edition, University Press of Florida, ISBN 0-8130-2691-1.

Bitzer, John A. Woerner, Ted A. *A4-Fibel* (English translation) Army Ballistic Missile Agency Redstone Arsenal, Al. 1957 ISBN 1-89-4643-14-3.

Bredt, Irene, Sanger, Eugen *A Rocket Drive for Long Range Bomber*s, 1944, reprinted 1952 by U. S. Government, Translation CGD-32, ASIN-B073RVFHXS.

Byrne, F. Doolittle, G. V. Hockenberger, R. W. “Launch Processing System,” Jan. 1976, IBM J. Research & Development.

Clark, John Drury, Ignition!: An Informal History of Liquid Rocket Propellants, 2018, ASIN-B076838QS2.

Congreve, William *The Details of the Rocket System,* 1814; avail: Museum Restoration Service, 1970

Corliss, William R. *NASA Sounding Rockets,* 1558-1968, NASA SP-4401.

Crossfield, A. Scott, and Blair, Clay *Always Another Dawn: The Story of a Rocket Test Pilot,* 1960, World Publishing Co. ASIN-B0010OYBXM.

Dornberger, Walter R. "The Rocket-Propelled Commercial Airliner"

Dyna-Soar: Hypersonic Strategic Weapons System, Research Report No 135. University of Minnesota, Institute of Technology, 1956.

Dumont, Brian, "An Introduction to the Athena Computer," May 16, 1969, Oregon State University, avail: https://archive.org/details/cc-69-09_athenaintro_may69

Dungan T. D., V-2: *A Combat History of the First Ballistic Missile*, 2005, ISBN-1594160120.

French, James R. *FIRING A ROCKET: STORIES OF THE DEVELOPMENT OF THE ROCKET ENGINES FOR THE SATURN LAUNCH VEHICLES AND THE LUNAR MODULE AS VIEWED FROM THE TRENCHES,* 2017, ISBN-1549688685.

GAO, *Evolved Expendable Launch Vehicle*, 2013, ASIN-B00AFBAVYY.

Haeussermann, Walter "Description and Performance of the Saturn Launch Vehicle's Navigation, Guidance, and Control System," July 1970, NASA TN D-5869.

Lardas, Mark, Palmer, Ian *Space Shuttle Launch System 1972–2004,* New Vanguard, 2012, ASIN-B01DPPWI74.

Lennick, Michael *Launch Vehicles – Heritage of the Space Race*, 2006, ISBN-1894959-28-0.

Ley, Willy and Aldrin, Buzz, *Rockets, Missiles, and Men in Space: A Definitive Account of the History of Space,* 1966, Viking Press, ASIN-B004H3G0WI.

Ley, Willy, Rockets, *The Future of Travel Beyond the Stratosphere*, 1945, Viking Press, ASIN- 0007E7IC2.

Ley, Willy, *Missiles, Moonprobes, and Megaparsecs*, 1964, ASIN-B000HWU3MG.

Ley, Willy, Satellites, *Rockets and Outer Space*, 1958, ASIN-B00005XUH1.

Ley, Willy *Rockets, Missiles, & Space Travel*, 1951, Viking Press, ASIN-B0000CI5RN.

Mullane, Mike *Riding Rockets, the Outrageous Tales of a Space Shuttle Astronaut*, 2007, Scribner, ISBN-0743276833.

NASA*, Saturn-V Flight Manual,* 2011, ISBN-1935700707.

NASA, *Vanguard, A History*, SP-4202, avail: https://history.nasa.gov/SP-4202.pdf

NASA, NASA Sounding Rockets, 1958-1968: A Historical Summary, 2014, ISBN-1502793970.

Ordway, Frederick I. *International Missile and Spacecraft Guide,* 1960, ASIN-B000MAEGVC.

Rosen, Milton W. *The Viking Rocket Story*, 1955, ASIN-B0007DVDZ6.

Sanger, Eugen, "Techniques of Rocket Flight," 1933, avail: www.aerospaceprojectsreview.com/blog/?p=2145

Sänger, Eugen; Sänger-Bredt, Irene "A Rocket Drive For Long Range Bombers", 1944, available:http://www.astronautix.com/data/saenger.pdf

Sanger, Eugen *Rocket Flight Engineering, 1933,* NASA Technical Translation, NASA TTF-223, 1965.

Seedhouse, Erik Virgin Galactic: The First Ten Years (Springer Praxis Books), 2015, ASIN-B00TY7N7F0.

Seedhouse, Erik *XCOR, Developing the Next Generation Spaceplane (Springer Praxis Books), 2016, ISBN-331926110X.*

Seedhouse, Erik *SpaceX's Dragon: America's Next Generation Spacecraft,* 2016, Springer, ISBN-3319215140.

Seedhouse, Erik Bigelow Aerospace: Colonizing Space One Module at a

Time, 2015, Springer, ISBN-3319051962.

Sivolella, Davide *The Space Shuttle Program: Technologies and Accomplishments* (Springer Praxis Books), 2017, ISBN-13319549448.

Stakem, Patrick H. *The History of Spacecraft Computers from the V-2 to the Space Station*, 2013, PRRB Publishing, ISBN-1520216181.

Stakem, Patrick H. *The Saturn Rocket and the Pegasus Missions, 1965,* 2013, PRRB Publishing, ASIN-B00BVA79ZW.

Stakem, Patrick H. *Rocketplanes to Space,* 2017, PRRB Publishing, ISBN-1549992589.

Stakem, Patrick H. *Visiting the NASA Centers,* 2017, PRRB Publishing, ISBN-154965120X.

Taylor, Travis, *Introduction to Rocket Science and Engineering*, 2009, ISBN-13-978-1420075281.

USAF, *US AIR FORCE FACT FILE DELTA II LAUNCH VEHICLE*, 2009, ASIN-B002HOQ8SK.

U. S. Government, *Historical Overview of the Space and Missile Systems Center 1954-2003 - Ballistic Missiles and Launch Vehicles, Atlas, Thor, Titan, EELV, Minuteman, Peacekeeper, MX, Delta, Satellites, MOL, Milstar,* 2015, ASIN-B00VMGVFQE.

U. S. Government, *Evolved Expendable Launch Operations at Cape Canaveral 2002-2009 - EELV Atlas V and Delta IV Rockets, Launch Operations, Commercial, Civil, and Military Space Operations, Complex 41,*2013, ASIN-B00DNQDALE.

von Braun, Wernher; Ordway, Frederick I. ; Durant, Fred *Space Travel: A History: An Update of History of Rocketry & Space Travel*, 1985, ISBN-0061818984.

von Braun, Wernher; Ordway, Frederick I. *The Rockets Red Glare*, 1976, ISBN-0-385-07847-1.

Walker, Chuck *Atlas, the Ultimate Weapon*, 2005, ISBN-1-894959-18-3.

Winter, Frank H. *America's First Rocket Company: Reaction Motors, Inc.,* 2017, ISBN-162410441X.

Young, Anthony *The Saturn V F-1 Engine: Powering Apollo into History*, 2008, ISBN-0387096299.

Zaloga, Steven J. *V-2 Ballistic Missile*, 1942-52, 2003, ASIN-B00AVH189Y.

Resources

- www.nasa.gov
- https://history.nasa.gov/ tindex.html#5
- https://www.nasa.gov/exploration/systems/orion/index.html
- https://history.nasa.gov/tindex.html#5
- http://klabs.org/history
- https://www.nasaspaceflight.com
- https://www.nasa.gov/sites/default/files/files/Orion_AZ_book.pdf
- Encyclopedia Astronautica, http://www.astronautix.com/
- current locations of Apollo hardware: https://nssdc.gsfc.nasa.gov/planetary/lunar/apolloloc.html
- Soyuz MS-1 http://space.skyrocket.de/doc_sdat/soyuz-ms.htm
- Vectors website - http://vc.airvectors.net/idx_sci.html
- http://history.redstone.army.mil/hist-1957.html

- Atlas-V Launch Services User's Guide, avail: https://www.ulalaunch.com/explore/gallery

- www.americanspacecraft.com

- The Delta Clipper Experimental, https://www.hq.nasa.gov/office/pao/History/x-33/dc-xa.htm

- Wikipedia, various

Glossary of terms

ABMA – (U. S.) Army Ballistic Missile Agency, Redstone Arsenal, Huntsville, Alabama.
Aerozine 50 – hypergolic liquid fuel for the Titan (Hydrazine and UDMH)
ARPA – Advanced Research Projects Agency.
ARS – American Rocket Society
CCB – Configuration Control Board; Common Core Booster.
CDR – Critical Design Review
Cyro – cyrogenic, extreme low temperature.
DCSS – Delta Cyrogenic Second Stage
DC-X – Delta Clipper, McDonnel-Douglas
DoD – (U.S.) Department of Defense
EELV – Evolvable Expendable Launch Vehicle
ELV – Expendable Launch Vehicle
EUS – Exploration Upper Stage (SLS)
FRR – Flight Readiness Review
GAO - (U.S.) Government Accountability Office
GEO – Geosynchronous orbit.
Gimbal – pivotal support, allows rotation; used in gyroscopes to measure rotation.
GPC – general purpose computer
Gpm – gallons per minute.
GSFC – NASA Goddard Space Flight Center, Greenbelt, MD.
GSLV – Geosynchronous Satellite Launch Vehicle.
GTO – geosynchronous transfer orbit.
HCO – heliocentric orbit
HEFT – Human Exploration Framework Team
HLLV – heavy lift launch vehicle
Hp – horse power, 746 watts.
Hypergolic – two substances that self-ignite, when mixed.
IAU – International Astronomical Union
ICBM – Intercontinental ballistic missile
ICPS – Interim Cyrogenic Propulsion Stage.
IGY – International Geophysical Year (July 1, 1957-Dec 31, 1958)
IRBM – intermediate range ballistic missile.
ISRO – Indian Space Research Organization.
ITP – Interoplanetary Transport System – Space-X.
IUS – Interim upper stage.

JATO – Jet Assisted take off (for heavy bombers).
JP-4 – jet fuel, 1951 spec MIL-DTL-5624. 50/50 gasoline-kerosene.
Kaman Line – official definition of space, 100 km.
KN – kiloNewtons (of force)
KSC – NASA Kennedy Space Center, launch site, Florida.
Lbf – pounds, force.
LC-37 – Launch Complex – 37 at KSC.
LEO – Low Earth Orbit.
LES – Apollo Launch Escape System.
LH_2 – liquid hydrogen.
LOX – liquid oxygen, boils at -297 F.
MARS – Mid-Atlantic Regional Spaceport, Near NASA's Wallops Flight Facility.
MCT – Mars Colonial Transporter – SpaceX.
MECO – main engine cut-off
Methalox – liquid methane, liquid oxygen engine.
Missile – a guided rocket.
MPS – main propulsion system
MSFC – NASA Marshall Space Flight Center, Huntsville, AL.
NASA – National Aeronautics and Space Administration.
NASCOM – NASA Communications Network. Worldwide, operated by GSFC.
NGL – Next Generation Launcher
NRL – U. S. Naval Research Lab.
NTO – nitrogen tetroxide.
PDR – Preliminary Design Review
POGO – longitudinal oscillation in liquid-fueled rocket motors that can lead to failure.
PSLV – polar satellite launch vehicle.
RAND – Research And Development Corporation, American Think-tank.
RBS – reusable booster system
RCS – reaction control system, for attitude control.
Redstone – Army missile developed by the von Braun team. Used for Mercury manned flights.
Redstone Arsenal – Army R&D facility in Huntsville, AL. Later became NASA MSFC.
RFMA – red fuming nitric acid, rocket fuel.
RLS – reusable launch system
RP-1 – rocket propellant-one, highly refined kerosene.

SCOUT – (U.S.) Solid Controlled Orbital Utility Test (rocket)
SI – System International – the metric system.
S-IC – first stage of the Saturn V
S-II – second stage of the Saturn V
S-IVB – third stage of the Saturn V
S-IV – second stage of Saturn 1 rocket.
SRB – solid rocket booster.
SRBM – short-range ballistic missile.
SSO – sun-synchronous orbit.
SSPO – sun-synchronous polar orbit.
SSRT – Single stage rocket technology (McDonnell Douglas)
SSTO – single stage to orbit
TLI – trans-lunar injection
TMI – trans-Martian injection
TSTO – two stage to orbit
TVC – thruster vector control (of attitude). Swiveling engines.
TV-x – Test Vehicle-x.
UDMH - Unsymmetrical dimethylhydrazine, a rocket fuel, hypergolic with nitrogen tetroxide.
ULA – United Launch Alliance (Lockheed Martin and Boeing).
VAFB – Vandenburg Air Force Base, California. Used for Polar launches.
Verne gun – used to launch an object into space.
Vernier – small rocket for steering and attitude control.

If you enjoyed this book, you might also be interested in some of these.

Stakem, Patrick H. *16-bit Microprocessors, History and Architecture*, 2013 PRRB Publishing, ISBN-1520210922.

Stakem, Patrick H. *4- and 8-bit Microprocessors, Architecture and History*, 2013, PRRB Publishing, ISBN-152021572X,

Stakem, Patrick H. *Apollo's Computers,* 2014, PRRB Publishing, ISBN-1520215800.

Stakem, Patrick H. *The Architecture and Applications of the ARM Microprocessors,* 2013, PRRB Publishing, ISBN-1520215843.

Stakem, Patrick H. *Earth Rovers: for Exploration and Environmental Monitoring,* 2014, PRRB Publishing, ISBN-152021586X.

Stakem, Patrick H. *Embedded Computer Systems, Volume 1, Introduction and Architecture*, 2013, PRRB Publishing, ISBN-1520215959.

Stakem, Patrick H. *The History of Spacecraft Computers from the V-2 to the Space Station*, 2013, PRRB Publishing, ISBN-1520216181.

Stakem, Patrick H. *Floating Point Computation*, 2013, PRRB Publishing, ISBN-152021619X.

Stakem, Patrick H. *Architecture of Massively Parallel Microprocessor Systems*, 2011, PRRB Publishing, ISBN-1520250061.

Stakem, Patrick H. *Multicore Computer Architecture,* 2014, PRRB Publishing, ISBN-1520241372.

Stakem, Patrick H. *Personal Robots*, 2014, PRRB Publishing, ISBN-1520216254.

Stakem, Patrick H. *RISC Microprocessors, History and Overview,* 2013,

PRRB Publishing, ISBN-1520216289.

Stakem, Patrick H. *Robots and Telerobots in Space Application*s, 2011, PRRB Publishing, ISBN-1520210361.

Stakem, Patrick H. *The Saturn Rocket and the Pegasus Missions, 1965,* 2013, PRRB Publishing, ISBN-1520209916.

Stakem, Patrick H. *Visiting the NASA Centers, and Locations of Historic Rockets & Spacecraft,* 2017, PRRB Publishing, ISBN-1549651205.

Stakem, Patrick H. *Microprocessors in Space*, 2011, PRRB Publishing, ISBN-1520216343.

Stakem, Patrick H. Computer *Virtualization and the Cloud*, 2013, PRRB Publishing, ISBN-152021636X.

Stakem, Patrick H. *What's the Worst That Could Happen? Bad Assumptions, Ignorance, Failures and Screw-ups in Engineering Projects, 2014,* PRRB Publishing, ISBN-1520207166.

Stakem, Patrick H. *Computer Architecture & Programming of the Intel x86 Family, 2013,* PRRB Publishing, ISBN-1520263724.

Stakem, Patrick H. *The Hardware and Software Architecture of the Transputer*, 2011,PRRB Publishing, ISBN-152020681X.

Stakem, Patrick H. *Mainframes, Computing on Big Iron*, 2015, PRRB Publishing, ISBN- 1520216459.

Stakem, Patrick H. *Spacecraft Control Centers*, 2015, PRRB Publishing, ISBN-1520200617.

Stakem, Patrick H. *Embedded in Space,* 2015, PRRB Publishing, ISBN-1520215916.

Stakem, Patrick H. *A Practitioner's Guide to RISC Microprocessor Architecture*, Wiley-Interscience, 1996, ISBN-0471130184.

Stakem, Patrick H. *Cubesat Engineering*, PRRB Publishing, 2017, ISBN-1520754019.

Stakem, Patrick H. *Cubesat Operations*, PRRB Publishing, 2017, ISBN-152076717X.

Stakem, Patrick H. *Interplanetary Cubesats*, PRRB Publishing, 2017, ISBN-1520766173 .

Stakem, Patrick H. Cubesat Constellations, Clusters, and Swarms, Stakem, PRRB Publishing, 2017, ISBN-1520767544.

Stakem, Patrick H. *Graphics Processing Units, an overview*, 2017, PRRB Publishing, ISBN-1520879695.

Stakem, Patrick H. *Intel Embedded and the Arduino-101, 2017,* PRRB Publishing, ISBN-1520879296.

Stakem, Patrick H. *Orbital Debris, the problem and the mitigation*, 2018, PRRB Publishing, ISBN-*1980466483.*

Stakem, Patrick H. *Manufacturing in Space*, 2018, PRRB Publishing, ISBN-1977076041.

Stakem, Patrick H. *NASA's Ships and Planes*, 2018, PRRB Publishing, ISBN-1977076823.

Stakem, Patrick H. *Space Tourism*, 2018, PRRB Publishing, ISBN-1977073506.

Stakem, Patrick H. *STEM – Data Storage and Communications*, 2018, PRRB Publishing, ISBN-1977073115.

Stakem, Patrick H. *In-Space Robotic Repair and Servicing*, 2018, PRRB Publishing, ISBN-1980478236.

Stakem, Patrick H. *Introducing Weather in the pre-K to 12 Curricula, A Resource Guide for Educators*, 2017, PRRB Publishing, ISBN-1980638241.

Stakem, Patrick H. *Introducing Astronomy in the pre-K to 12 Curricula, A Resource Guide for Educators*, 2017, PRRB Publishing, ISBN-198104065X.
Also available in a Brazilian Portuguese edition, ISBN-1983106127.

Stakem, Patrick H. *Deep Space Gateways, the Moon and Beyond*, 2017, PRRB Publishing, ISBN-1973465701.

Stakem, Patrick H. *Exploration of the Gas Giants, Space Missions to Jupiter, Saturn, Uranus, and Neptune*, PRRB Publishing, 2018, ISBN-9781717814500.

Stakem, Patrick H. *Crewed Spacecraft*, 2017, PRRB Publishing, ISBN-1549992406.

Stakem, Patrick H. *Rocketplanes to Space*, 2017, PRRB Publishing, ISBN-1549992589.

Stakem, Patrick H. *Crewed Space Stations,* 2017, PRRB Publishing, ISBN-1549992228.

Stakem, Patrick H. *Enviro-bots for STEM: Using Robotics in the pre-K to 12 Curricula, A Resource Guide for Educators,* 2017, PRRB Publishing, ISBN-1549656619.

Stakem, Patrick H. *STEM-Sat, Using Cubesats in the pre-K to 12 Curricula, A Resource Guide for Educators*, 2017, ISBN-1549656376.

Stakem, Patrick H. *Lunar Orbital Platform-Gateway*, 2018, PRRB Publishing, ISBN-1980498628.

Stakem, Patrick H. *Embedded GPU's*, 2018, PRRB Publishing, ISBN-1980476497.

Stakem, Patrick H. *Mobile Cloud Robotics*, 2018, PRRB Publishing, ISBN- 1980488088.

Stakem, Patrick H. *Extreme Environment Embedded Systems,* 2017, PRRB

Publishing, ISBN-1520215967.

Stakem, Patrick H. *What's the Worst, Volume-2*, 2018, ISBN-1981005579.

Stakem, Patrick H., *Spaceports*, 2018, ISBN-1981022287.

Stakem, Patrick H., *Space Launch Vehicles*, 2018, ISBN-1983071773.

Stakem, Patrick H. *Mars*, 2018, ISBN-1983116902.

Stakem, Patrick H. *X-86, 40th Anniversary ed*, 2018, ISBN-1983189405.

Stakem, Patrick H. *Lunar Orbital Platform-Gateway*, 2018, PRRB Publishing, ISBN-1980498628.

Stakem, Patrick H. *Space Weather*, 2018, ISBN-1723904023.

Stakem, Patrick H. *STEM-Engineering Process*, 2017, ISBN-1983196517.

Stakem, Patrick H. *Space Telescopes,* 2018, PRRB Publishing, ISBN-1728728568.

Stakem, Patrick H. *Exoplanets*, 2018, PRRB Publishing, ISBN-9781731385055.

Stakem, Patrick H. *Planetary Defense*, 2018, PRRB Publishing, ISBN-9781731001207.

Patrick H. Stakem *Exploration of the Asteroid Belt*, 2018, PRRB Publishing, ISBN-1731049846.

Patrick H. Stakem *Terraforming*, 2018, PRRB Publishing, ISBN-1790308100.

Patrick H. Stakem, *Martian Railroad,* 2019, PRRB Publishing, ISBN-1794488243.

Patrick H. Stakem, *Exoplanets,* 2019, PRRB Publishing, ISBN-1731385056.

Patrick H. Stakem, *Exploiting the Moon,* 2019, PRRB Publishing, ISBN-1091057850.

Patrick H. Stakem, *RISC-V, an Open Source Solution for Space Flight Computers,* 2019, PRRB Publishing, ISBN-1796434388.

Patrick H. Stakem, *Arm in Space*, 2019, PRRB Publishing, ISBN-9781099789137.

Patrick H. Stakem, *Extraterrestrial Life*, 2019, PRRB Publishing, ISBN-978-1072072188.

Patrick H. Stakem, *Space Command*, 2019, PRRB Publishing, ISBN-978-1693005398.